Horizontal-Vertical Coupling of a Building Frame System in Shake Table Testing to 3D Motions

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OVERVIEW

A large-scale, shake-table test program was conducted with a goal to promote rapid spread of base isolation systems in Japan and the U.S. A small steel frame building with and without base isolation was subjected to 2D and 3D shaking at E-Defense. Coupling of the horizontal and vertical response as well as high intensity slab vibration contributed to nonstructural damage in the building. Strong coupling in a configuration with triple pendulum bearings (TPB) was shown to result from the friction mechanism in the bearings. However, the source of coupling in a configuration with a hybrid isolation system (lead rubber bearings or LRB and cross-linear rolling bearings) and the fixed-base building configuration has not yet been explained.

OBJECTIVES

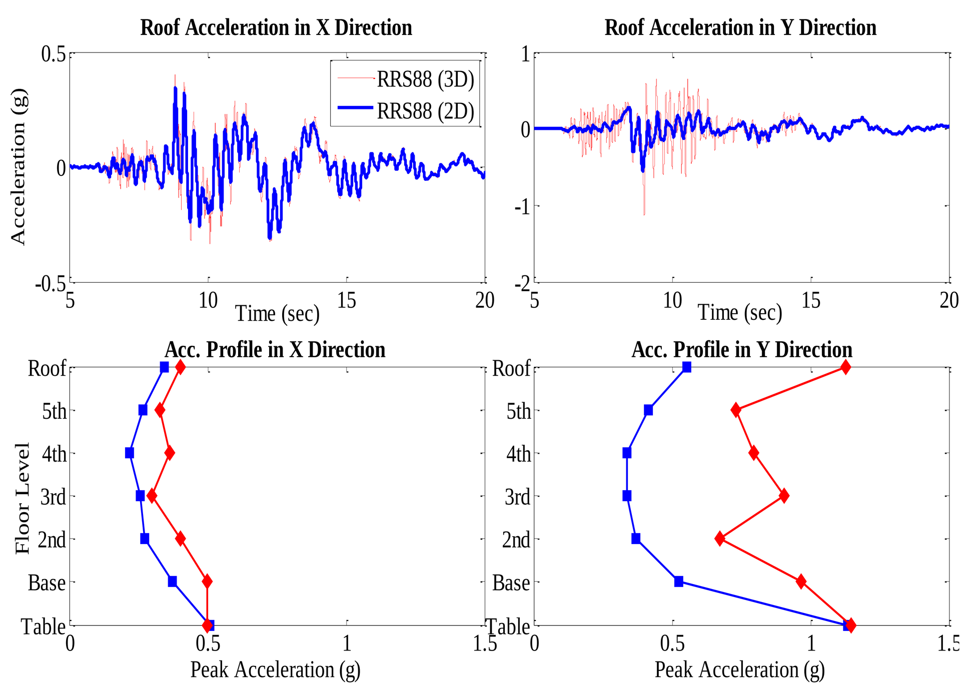
1. Explain the sources of horizontal-vertical coupling in the fixed-base and hybrid-LRB configurations due to coupling in the building frame-slab system.
2. Validate observed floor and slab accelerations through computational simulation.
3. *Determine the potential for coupling in fixed-base vs. base-isolated buildings (ongoing).*

Test Building Characteristics

- ✓ Five story steel moment frame with concrete floor slabs
  - 10 x 12 m in plan, 15 m tall
  - Asymmetric frame configuration
  - Added mass in the east bay at roof
- ✓ Interior walls, suspended ceilings and sprinkler piping installed on upper floors. Two enclosed rooms with contents.
- ✓ Designed as Value Added Building in Japan
  - $T = 0.7$ sec, Yield Base Shear = $0.7W$
- ✓ Hybrid isolation system characteristics
  - $T_{eff} = 2.6$ sec, $\beta_{eff} = 10\%$ at disp = 0.6 m

Influence of Vertical Shaking on the Response

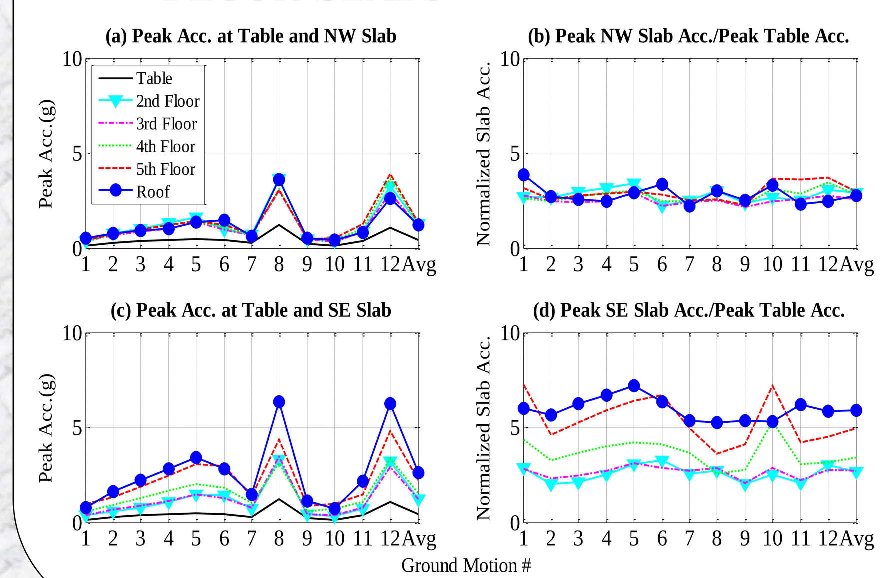
2D vs 3D Shaking in Fixed-Base



Observed in Both Configurations

- ✓ Horizontal accelerations were amplified in 3D shaking compared to 2D shaking.
- ✓ Vertical accelerations in slabs were amplified by average factor of 3-6 relative to ground.
- ✓ Damage in nonstructural components was observed from combined effect of horizontal floor accelerations and vertical slab vibration.

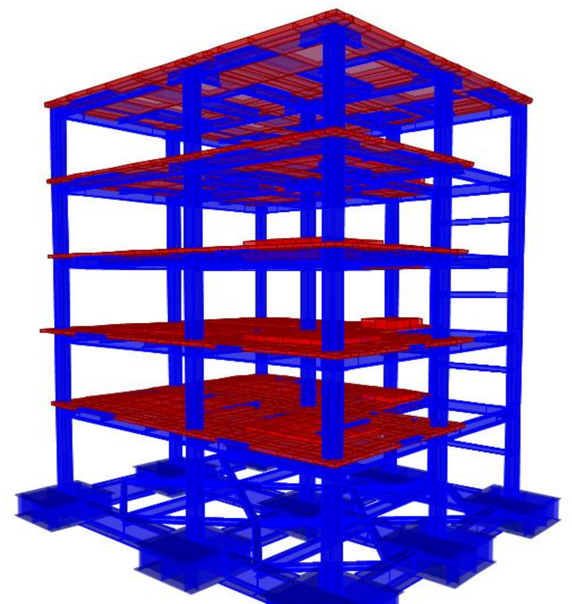
Vertical Accelerations in Floor Slabs

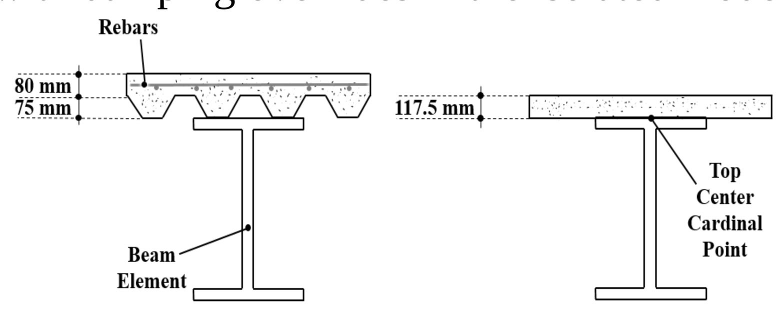


Damage to Nonstructural Components

Modeling Assumptions for SAP Building Model

- ✓ Beams and columns are modeled with linear frame elements using centerline approach
- ✓ Slabs are modeled with linear shell elements
  - Insertion points used to offset shells from frames and capture the composite bending stiffness
  - Dense discretization of shells for discrete mass distribution
  - Corrugated steel with concrete decking represented by an effective thickness
- ✓ Partial diaphragm constraint (applied to select nodes) calibrated to experimental response
- ✓ Constant modal damping applied to superstructure with damping overrides in the isolated modes

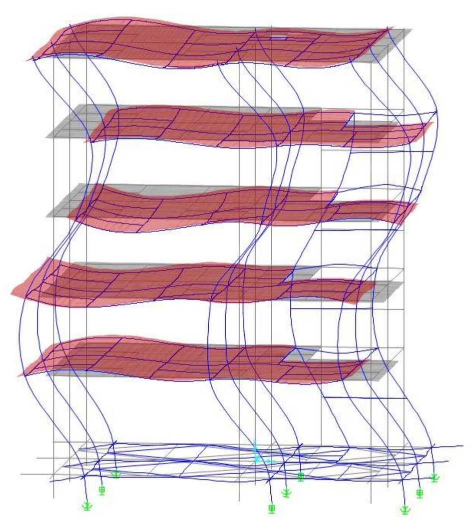




- ✓ Isolators modeled with rigid links
  - Bidirectionally coupled Bilinear horizontal force deformation
  - Vertically linear with manufacturer provided tension and compression stiffnesses

Modal Analysis

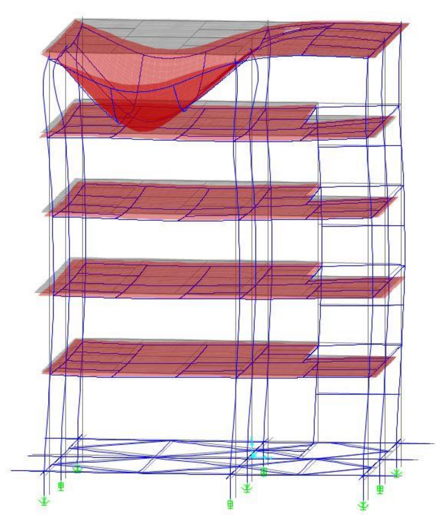
Modal analysis revealed horizontally-vertically coupled modes (e.g. vertical slab vibration is apparent in a primarily horizontal mode) in both configurations. The coupling occurred in the y-direction third structural mode.

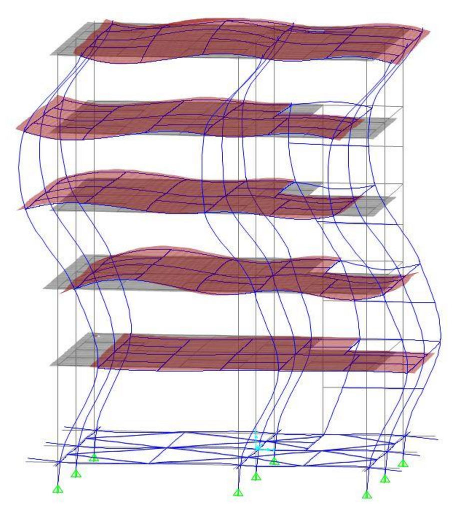


Base-Isolated Configuration

3rd Structural Mode (Coupled)
f = 9.35 Hz, T = 0.11 sec

1st Vertical Mode
f = 7.82 Hz , T = 0.13 sec

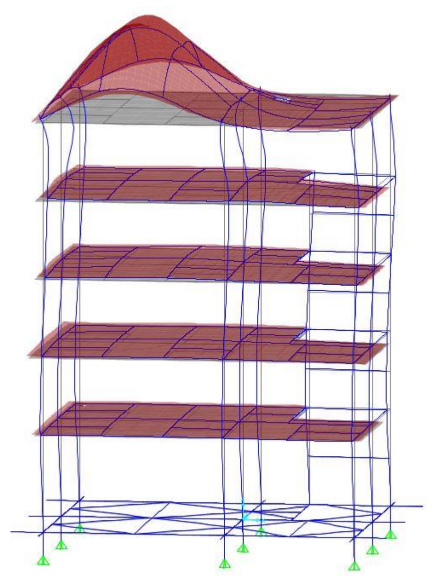




Fixed-Base Configuration

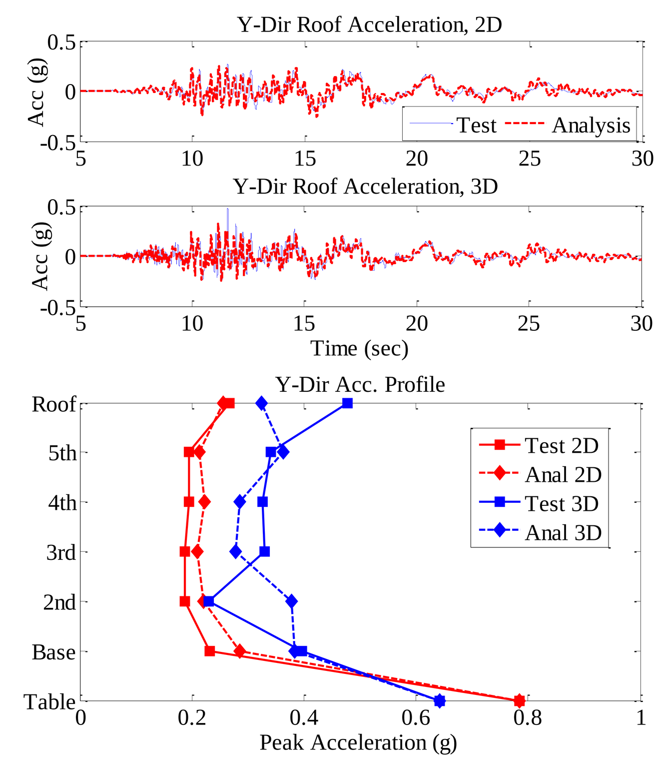
3rd Structural Mode (Coupled)
f = 8.58 Hz, T = 0.12 sec

1st Vertical Mode
f = 7.04 Hz, T = 0.14 sec

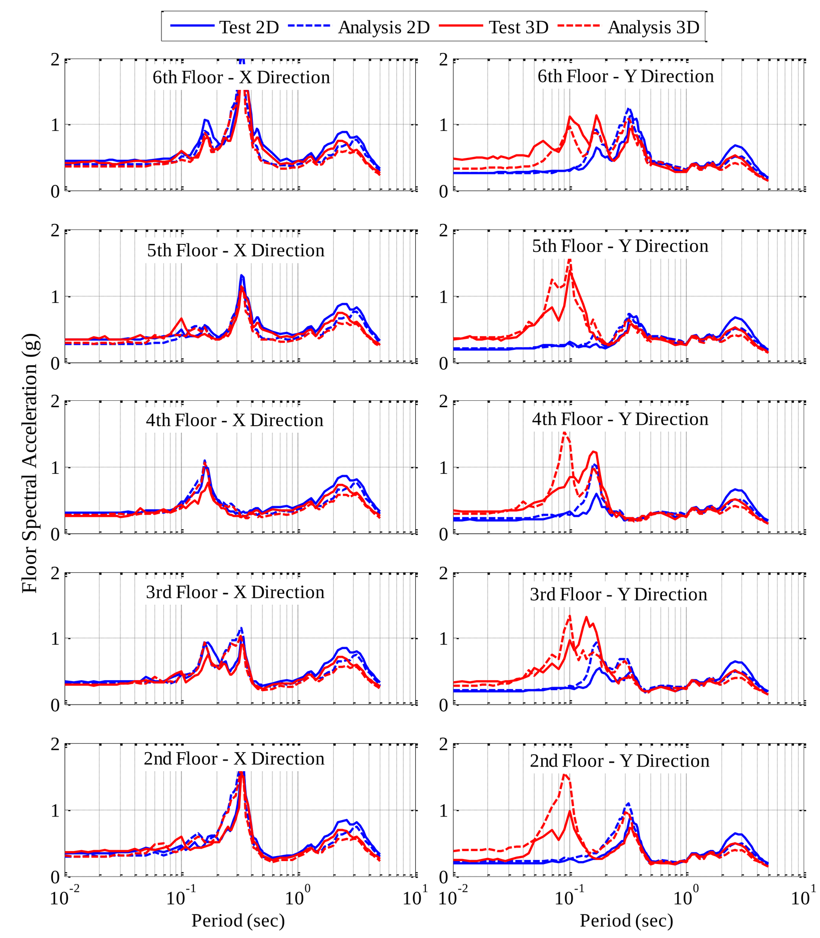


Computational Validation of Experimental Results

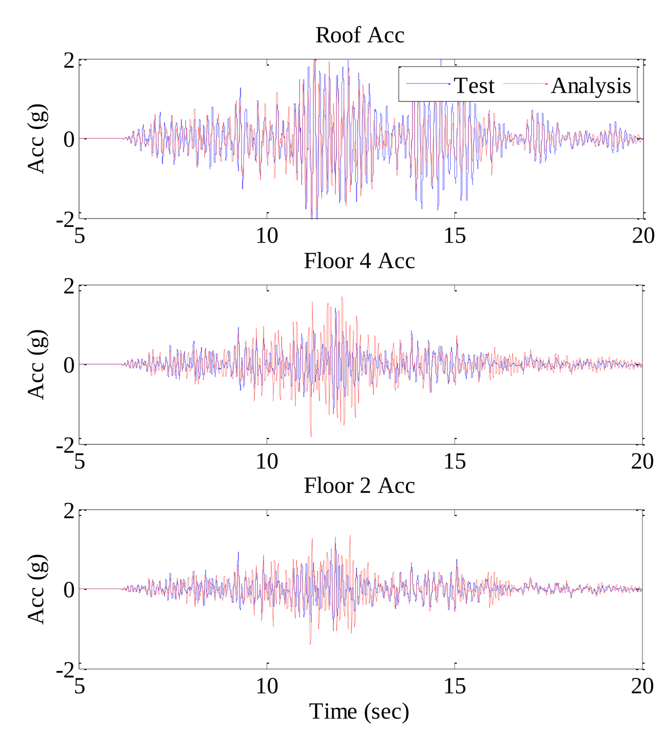
Floor Accelerations



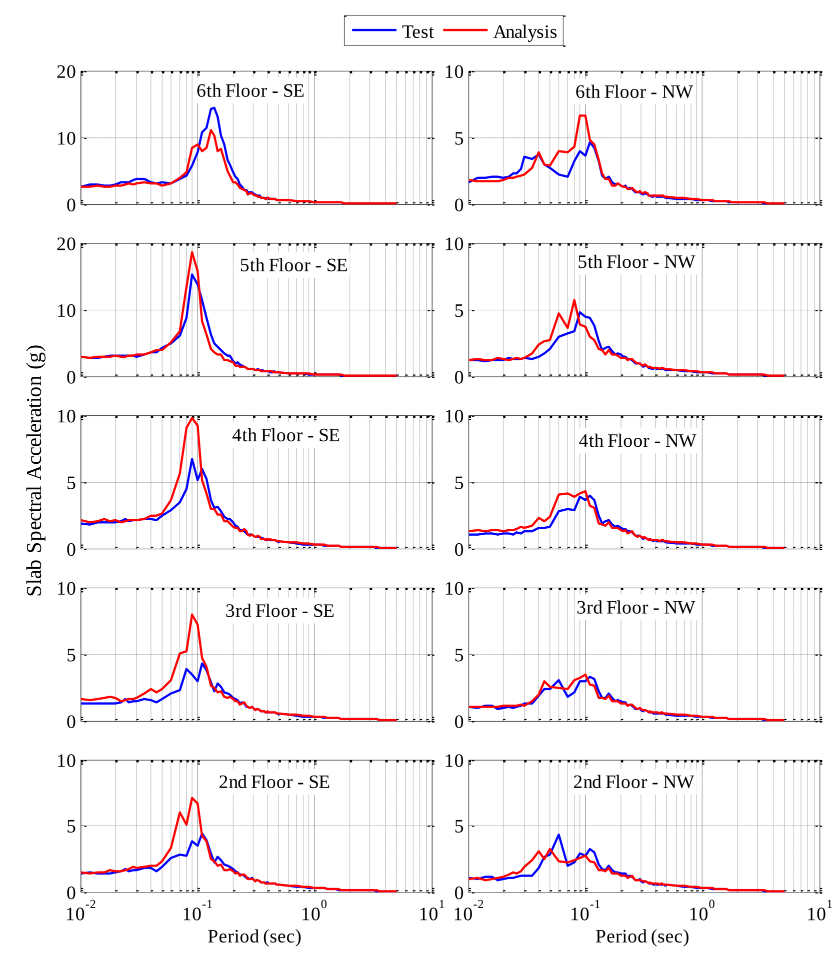
Horizontal Floor Spectra



Slab Accelerations



Slab Spectra



Conclusion: Horizontally-vertically coupled modes may arise in buildings with irregular geometry or mass distribution. In coupled systems, vertical shaking amplifies horizontal response. When combined with strong slab vibration, this can lead to nonstructural damage even in well-designed base-isolated buildings. The effects can be predicted through computational simulation.